ENHANCEMENT OF HUMIDIFICATION USING DIFFERENT CARRIER'S GASES INJECTION THROUGH WATER BED: ANUMERICAL INVESTIGATION

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ABSTRACT

The present study has presented an approach attempting for enhancement of mass transfer between a continuous gas phase and liquid phase in a non-packed humidification towers by injection of different carrier's gases such as air, carbon dioxide and helium through water bed. The computational technique utilized is a two-dimensional Navier-Stokes solver with free-surface simulation in Piecewise Linear Interface Construction method to compute the bubble shape, the two-dimensional two-phase flow field and pressure on a water bed. This work studied the influence of the operating conditions such as the water bed temperature and carrier's gas type on water vapor content in thecarriergas. The present study included also determines of the overall pressure drop of the carrier gases through water bed, and humidification efficiency. As for the heat and mass transfer performance of the humidification tower, the effect of water bed temperature on the overall gas phase heat and mass transfer coefficient was investigated for each gas in order to assess the effect of injection technique. It has been found that the mass transfer coefficient increases with increasing carrier gas molecular weight. The obtained maximum humidification efficiency of the helium was about 87%. The pressure drop is about 514 Pa for helium and 472 Pa for carbon dioxide at a water bed temperature 353 K.

Keywords: Air injection; CFD; Humidification; Carrier gas.

1. INTRODUCTION

When gas that is not saturated with water passesacross a wetted surface, the surface temperature will drop because of evaporation of water. This drop in temperature together with the temperature of the gas stream gives a measure of the humidity of the gas. For many years, psychrameters based on this phenomenon have been used very successfully for increasing the humidity of air under the usual conditions of temperature and pressure. In recent years, it was found necessary to enhance the mass transfer between liquid and gas phases to provide a high moisture content. This led to a need for knowledge of the humidification behavior and properties based on contact of carrier gases and liquid. The injection process of carrier gases such as air and helium through water bed is a promising humidification technique increase the humidification efficiency in many engineering applications including saline water desalination, medicine,

agriculture and air conditioning.
A promising technology for small scale seawater desalination is the humidification dehumidification (HDH) system. This technology has been widely investigated in recent years. Since existing HDH systems have very high specific energy consumption, it is important to invent new ways to increase the energy efficiency of these systems. Even for these relatively high efficiency systems the dehumidifier is expected to be large, owing to the large thermal resistance associated with the presence of anon-condensable carrier gas (air) in the system. Narayan et al. [1] Demonstrated a changing of the carrier gas from the air to helium a potential solution to thermal resistance associated with the presence of anon-condensable carrier gas (air) problem. El-Agouz and Abugderah [2] investigated an experimental of humidification process by air passing through seawater is presented. The main objective of this work was to determine the humid air behavior through a single-stage of heating-humidifying processes. They studied the influence of the operating conditions such as the water temperature, the water head difference, the air velocity and the inlet air temperature to evaporator chamber on the vapor content difference and humidification efficiency. The obtained maximum vapor content difference of the air was about 0.222 kgw/kga at 75 °C for water and air.

Abu Arabi and Reddy [3] carried out performance evaluation for desalination processes based on the HDH principle with different carrier gases through modeling and simulation techniques. Different carrier gases besides air were used in the performance evaluation: hydrogen, helium, neon, nitrogen, oxygen, argon and carbon dioxide. They found that helium gives much better heat flux than air, while carbon dioxide gives much better mass flow.Abd-ur-Rehman, and Al-Sulaiman [4] develop an analytical model for bubbler humidifier to study the enhancement on the performance of the HDH water desalination system. They indicate that the increase in air inlet velocity significantly enhances the heat and mass transfer coefficient. The increase in the temperature difference between the air and water stream increases the efficiency of the humidifier. Khalil et al. [5] investigated an experimental study of a solar water desalination using an air bubble column humidifier. There results showed that the daily productivity, efficiency and gain output ratio are 21 kg, 63%, and 0.53 respectively; at inlet water temperature is 62 °C.
Gas hold up is one of the most important parameters characterizing the hydrodynamics of bubble columns. It can be defined as the percentage by volume of the gas in the two or three phase mixture in the humidifier [6].Moshtari et al [7] investigated gas hold up, bubble size and effect of sparger type in different gas velocity; liquid phase and gas phase were water and air respectively. They indicated that with increasing the superficial gas velocity, the total gas holds up increases. Also perforated-type sparger increases the diameter of bubbles up to 35% and decreases gas hold up to about 40% respectively.

In the literature no study has been found that improves the humidification efficiency by gas injection through water bed by using other carrier gases instead of air. In this study a water-gas system with forced convection is numerically modeled and simulations are conducted for assessing the system performance with different carrier gases by evaluating the humidification efficiency and power consuming. The parameters considered for this study are the water bed temperature and influences the carrier gas type.Selecting helium and carbon dioxide as a carrier gas are based on its thermo-physical properties compared with various gases which could possibly be used in humidification system.

2. NUMERICAL MODELING APPROACHES

The two-phase flow-field around inside the humidifier with the Free Surface simulation in Piecewise Linear Interface Construction (PLIC) method is modeled computationally using a three-dimensional Navier-Stokes code (CFDRC [8]). The governing equations are discretized on a structured grid using an Upwind Difference (UD) scheme. For different conditions, the bubble shape, the two-dimensional field, temperature, density and the pressure variation are computed.

2.1 Problem Formulation

Based on the basic philosophical equations thatareequation of the mass, momentum and energy conservations as follows:

Mass Conservation

$$\frac{\partial \rho}{\partial t} + div(\rho V) = 0 \quad (1)$$

Momentum Conservation

$$\frac{\partial (\rho u)}{\partial t} + div(\rho V u) = -grad(P) + \mu \nabla^2 u \quad (2$$

Energy Conservation

$$\frac{\partial (\rho C_p T)}{\partial t} + div(\rho V C_p T) = div[K grad(T)] \quad (3)$$

For a two fluid system,the basis of the method used to simulate the Free Surface in CFDRC code is the Volume-Of-Fluid (VOF) method. The volume fraction *F* (of water in this case) in each grid cell is stored as a scalar variable. Flow field and distribution of *F*are determined by solving the passive transport equation:

$$\frac{\partial F}{\partial t} + \nabla \bullet \vec{v} F = 0 \quad (4)$$

If its value is 1, the cell is full, if 0 it is empty, and if 0 < *F* < 1, then the cell contains the free surface.

The average value of any volume specific quantity, □, in a computational cell can be computed from the value of *F* in accordance with:

$$\phi = F\phi_2 + (1-F)\phi_1 \quad (5)$$

For an intensive quantity, Equation (5) can be extended to include the effect of density, □:

$$\phi = [F\rho_2 \phi_2 + (1-F)\rho_1 \phi_1] / \rho_{mix} \quad (6)$$

where subscripts 1 and 2 refer to the two fluid phases respectively.

MASS AND HEAT TRANSFER COEFFICIENT CALAULATION

Based on two-film theory, the overall mass transfer coefficient (k_l) can be conceptualized as the sum of resistance on the liquid and gas sides of the carrier gas-water interface:

$$k_l = \left(\frac{1}{k_w} + \frac{1}{k_{cg}}\right)^{-1} \quad (7)$$

where k_w = liquid-phase mass transfer coefficientandk_{cg} = gas-phase mass transfer coefficient which are defined as[10]:

$$k_w = 2\sqrt{\frac{D_{AB}}{\pi t}} \quad (8)$$

$$k_{cg} = \frac{D_{AB}}{0.5 d_b} \quad (9)$$

Where, t represents the surface renewal time that can be calculated as follows:

$$t = \frac{d_b}{u_c} \quad (10)$$

The bubble diameter $d_b$is given by[11]:

$$d_b = \left[\frac{6\sigma d_{ih}}{g(\rho_w - \rho_{cg})}\right]^{1/3} \quad (11)$$

Liquid circulation velocity $u_c$can be calculated by the following correlation[12]:

$$u_c = 1.36 gH (u_{cg} - \varepsilon_{cg} u_b) \quad (12)$$

Bubble velocity u_b, can be calculated based on the following correlation[13]:

$$u_b = \sqrt{\frac{2\sigma}{\rho_l d_b} + \frac{g d_b}{2}} \quad (13)$$

Heat transfer coefficient h_t can be calculated by introducing Lewis factor as follows:

$$h_t = Le^{2/3} \rho_w c_{p,w} k_l \quad (14)$$

where, Le is Lewis number for carrier gas-water system and defined as

$$Le = \frac{\alpha}{D_{AB}}$$

(15)

where D_{AB} and α are mass and thermal diffusivities respectively.

2.2 Problem Statement and Grid Structure

The problem domain considered is depicted schematically in Figure (1) and refers to the two-dimensional flow of gas injection from 5 mm diameter fifteen holes in the bottom of a water bed with 50 mm height and 300 mm width. The Cartesian coordinate is chosen and the origin.

The present study considers the unsteady-state, laminar, two-phase, two-dimensional, and gas injection from holes. All the thermo-physical properties are assumed to be constants. The multi block calculation system approach is applied. The structured grids are divided into fourteen 2-D blocks.

Commercial software (CFDRC) was used with a structural grid of a total number of nodes of 217,120 using the multi-block system approach. The structured grids are divided into seventeen2-D blocks. The practical applications considered are two-dimensional. Grid spacing is non-uniform, being concentrated near the injection holes because of the large velocity, density and pressure gradients in that region. The dimensions of the grids in physical domain are about 45.5 cm lengthand 29.5width as shown in Figure (2).

2.3 Boundary and Initial Conditions

The inlet boundary and initial conditions of injection gas are10 m/s axial velocity with pressure 100N/m^2 and outlet boundary condition is fixed pressure equal to the atmospheric pressure. All blocks are starting with water except thefifteen injection pipes are completely full of gas.The gas domains have a constant initial temperature of 300 K. The water bed has a constant initial temperature of 293 or 323 or 353 K, according to the test case. The physical time step is taken as 10^{-4} second for the unsteady flow computations in order to resolve accurately the transients of the bubble formation.

3. CARRIER GASES PROPERTIES

In this study different carrier gases are considered, namely air, helium and carbon dioxide. So, in this section the thermophysical and psychometric properties will be presented.

3.1 Psychrometric properties

The mass of water vapor present in a unit mass of humid carrier gas or the humidityratio can be expressed as[14]:

$$\omega_{cg} = \frac{m_{v,w}}{m_{d,cg} + m_{v,w}} = \frac{m_{v,w}}{m_{h,cg}} = \frac{V\rho_{v,w}}{V\rho_{h,cg}} = \frac{\rho_{v,w}}{\rho_{h,cg}} \quad (16)$$

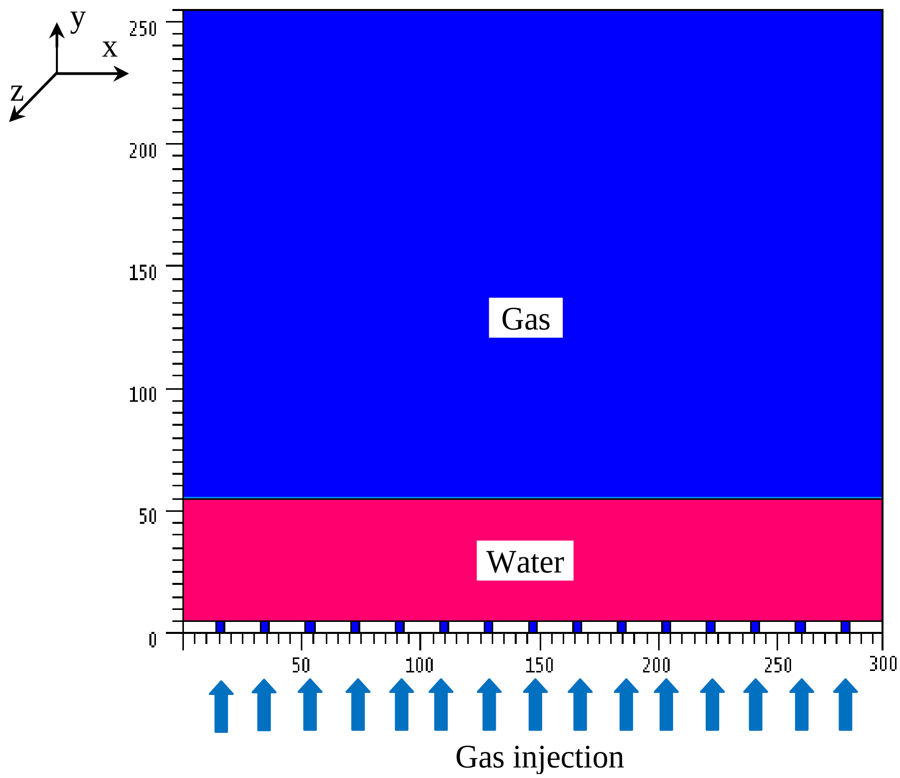


Fig. 1: Problem domain details.

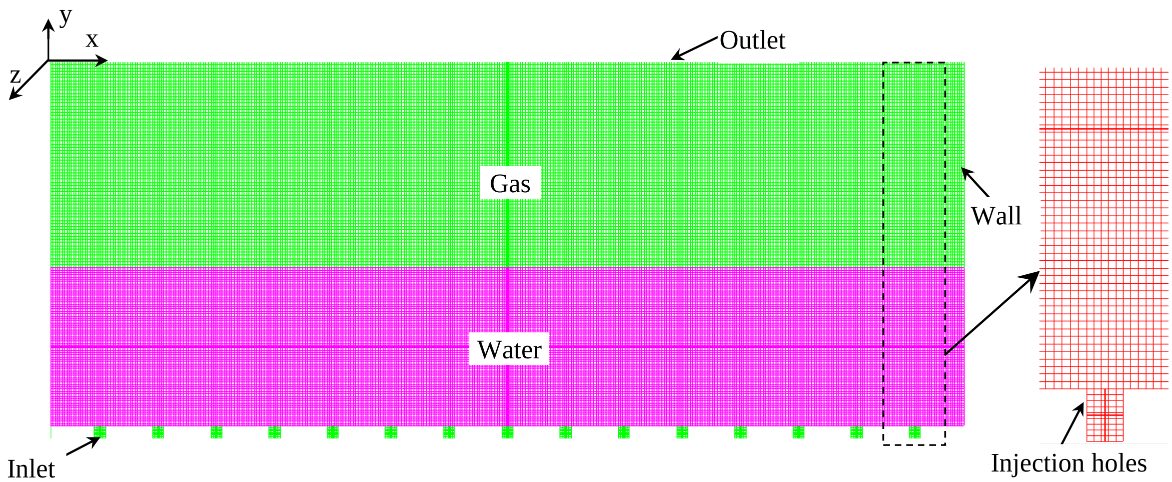


Fig. 2: Structured grid of flow field

3.2 Thermophysical properties

Table (1) shows all the important thermophysical properties for air, helium, and carbon dioxide at *T*=25˚C and *P*=1 atm. It is observed that carbon dioxide has a much higher molecular weight than the other gases in consideration, about 1.5 and 11 times that of air and helium. The thermal conductivity is especially important because a higher value will help improve the mass transfer coefficient between carrier gas and water bed [3].

Table 1: Thermophysical properties of different carrier gases at 25°C and atmospheric pressure

Carrier gas	M (g/mol)	k (W/m.K)	c_p (J/kg.K)	ρ (kg/m^3)
Air	28.97	0.02551	1.005	1.169
He	4.003	0.1502	5.193	0.1615
CO_2	44.01	0.01657	0.8415	1.1775

4. RESULTE AND DISCUSSIONS

4.1 Model results validation

The result of carrier gases type and water bed temperature effects on productivity had been validated with previous work [2], [3], [4] and [7]. The present numerical model had been compared and a good agreement with experimental data trend had been obtained. In addition, experimental replication of the proposed system is currently underway to validate model assumptions and predictions.

As mentioned before, the humidification process of gases by water using aninjection of different carrier gases through water is affected by water bed height, water bed temperature and theinjected gas conditions (thermo-physical properties, axial velocity and pressure). For the above different conditions, the bubble shape, the two-dimensional flow field and the density variation on the outlet were determined numerically. The effects of carrier gas and water bed temperature are presented in this paper for air, carbon dioxide and helium and 293, 323 and 353 K respectively. So, there are three sets of numerical results for each gas type (air, CO_2 and He) that are computed for the same other conditions.

Bubbles Formation and Density Variation

Figures (3-5) display the iso-density computational contours for gas bubbleformation after certain time periodfrom gas injection starting for different values of water bed temperature T_{wb} = 293, 323 and 353 K. The numerical results demonstrate that the bubble formation has density gradient form minimum value of gas density to a maximum value of water density.

Mass transfer coefficient

Figure (6) presents the humidification efficiency (η_h) with the variation of the temperature difference between water bed and carrier gas $(T_{wb} - T_{cg})$. Helium is achieved high mass transfer coefficient. Explanation of these findings is the following: the mass transfer coefficient between injected gas and water bed increases with a decrease in the molecular weight of the carrier gas. Also, the mass transfer coefficient increases with theincrease of water bed temperature.

Humidification efficiency

The ratio of actual to maximum vapor content difference in evaporator chamber is defined as the humidifier efficiency and is given by:

$$\eta_h = 100\frac{\omega_{cgo} - \omega_{cgin}}{\omega_{cgs} - \omega_{cgin}} \qquad (17)$$

Where ω_{cgin} and ω_{cgo} are respectively the humidity of gas at the inlet and the outlet of the humidifier. ω_{cgs} is the saturation humidity corresponding to the actual humidification process.This definition of the efficiency, also used by [15], [16] and [4]. Figure (7) presents the humidification efficiency (η_h)with variation of the temperature difference between water bed and carrier gas $(T_{wb} - T_{cg})$.Heliumis found to be the best carrier gas to achieve high humidification efficiency and desalinated water under the same operating conditions.Also, the humidification efficiency increases with the increase of water bed temperature. Explanation of these findings is the following: the increase of water bed temperature increases the bubble rise velocity and bubble size. In addition, the increase in the number of gas bubbles increases the rate of interface area, which increases the productivity.

PRESSURE VARIATION

Figures (8-10) display the computational contours for pressure variation after certain time period starting from the injection of carrier gas for different values of water bed temperature.

PRESSURE DROP

Figure (11) shows the pressure drop in carrier gases through water bed variations as a function of temperature difference between water bed and carrier gas $(T_{wb} - T_{cg})$while the outlet air pressure is atmospheric pressure. The figure illustrates that the increase of carrier gas molecular weight decreases the pressure drop. The higher molecular weight increases thetotal mass flow of carrier gas per unit of water vapor produced. This leads to adecrease of carrier gas pressure drop through water bed. The pressure drop maximum value is for helium about 586 Pa and 538 Pa for carbon dioxide at a water bed temperature 293 K.

Water temperatureplays an important role in pressure drop through a water bed. Theviscosity of water changes withtemperature. This is due to less of flow resistance. For constant carrier gas flow rate, theamount of pressure drop through the water bed will decrease astemperature increases. The pressure drop minimum value is for helium about 514 Pa and 472 Pa for carbon dioxide at a water bed temperature 353 K.

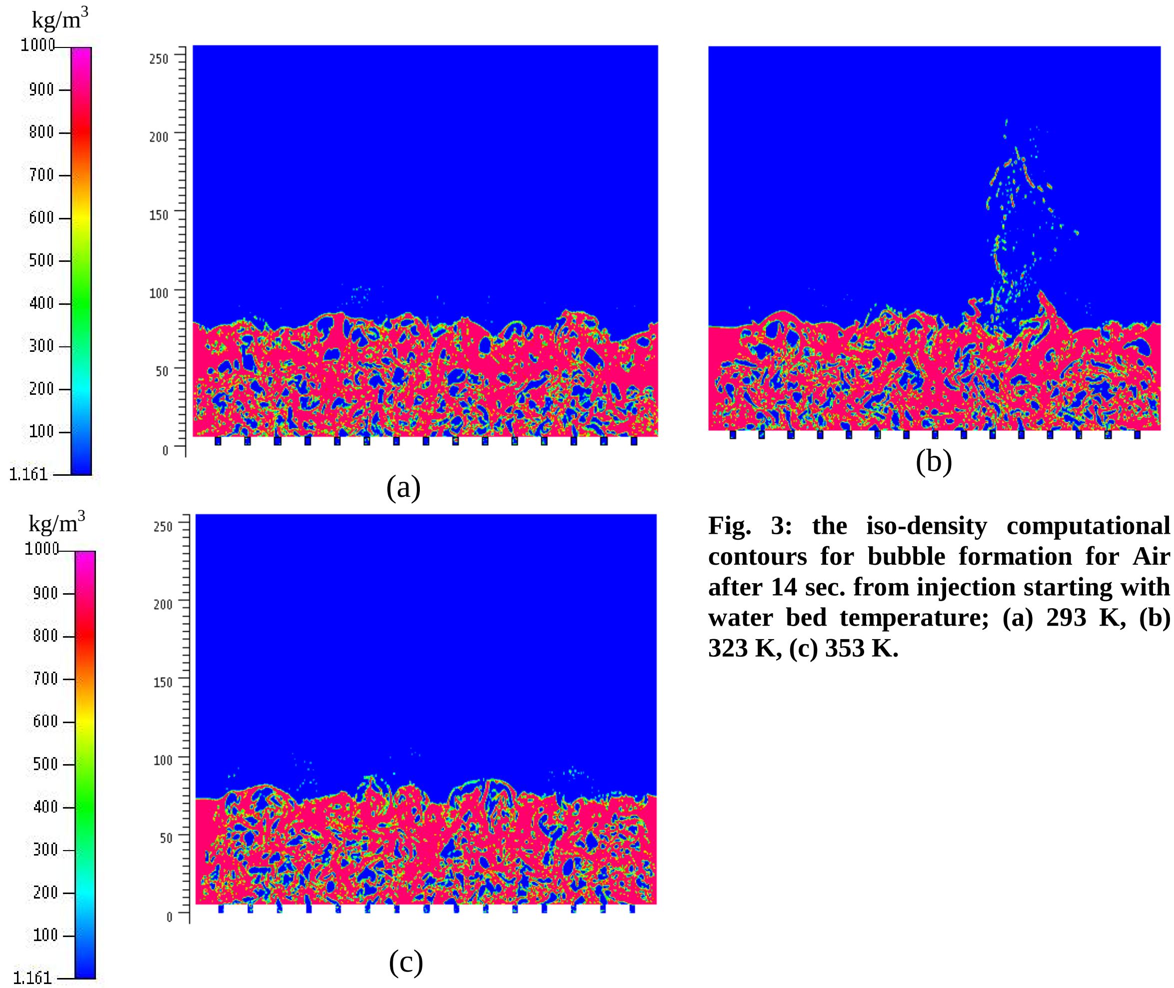
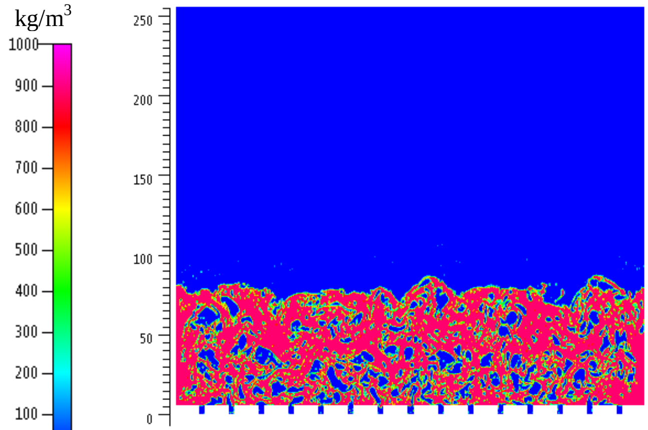


Fig. 3: the iso-density computational contours for bubble formation for Air after 14 sec. from injection starting with water bed temperature; (a) 293 K, (b) 323 K, (c) 353 K.



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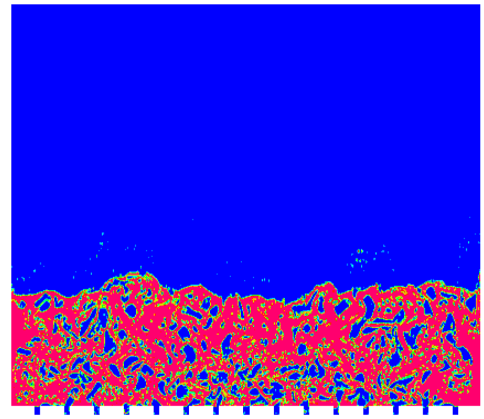

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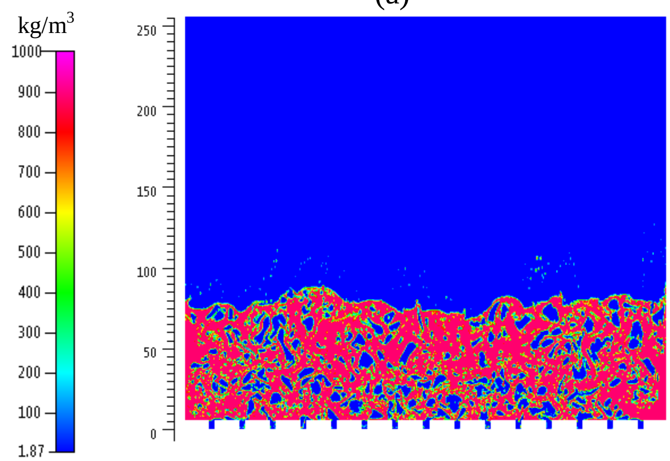
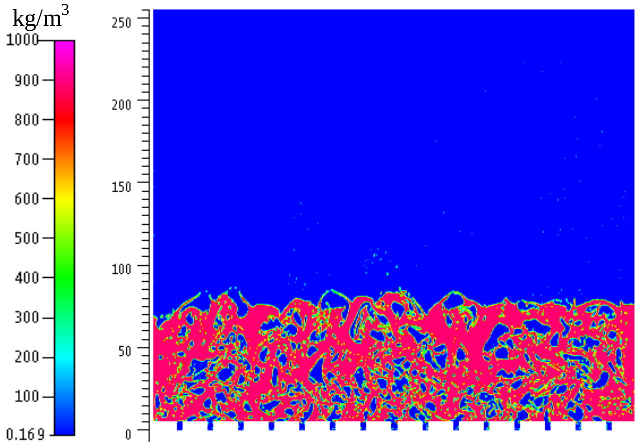


(c)

Fig. 4:the iso-density computational contours for bubble formation for Carbon dioxide after 15 sec. from injection starting with water bed temperature; (a) 293 K, (b) 323 K, (c) 353 K.



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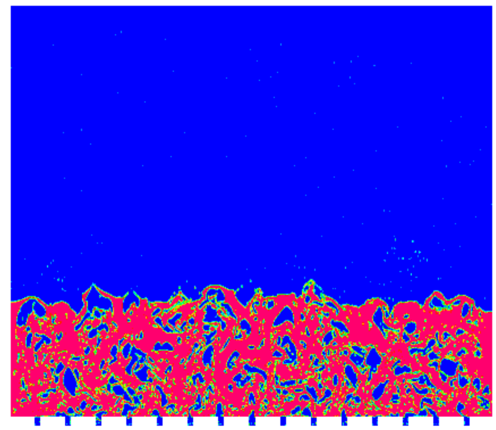

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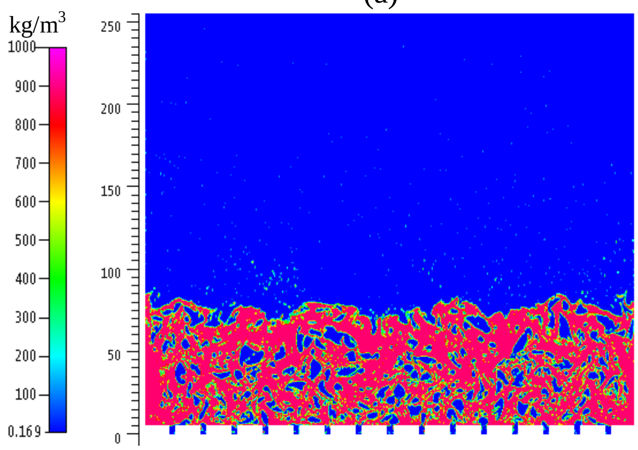

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Fig. 5: the iso-density computational contours for bubble formation for Helium after 14 sec. from injection starting with water bed temperature; (a) 293 K, (b) 323 K, (c) 353 K.

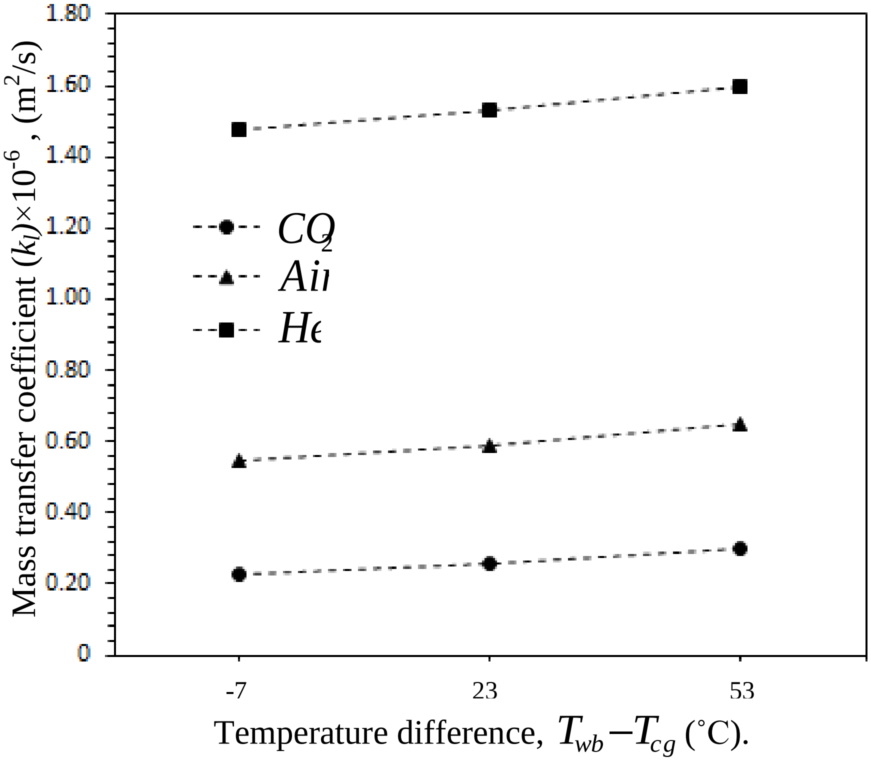


Fig. 6: Mass transfer coefficient variations as a function of temperature difference between water bed and carrier gas.

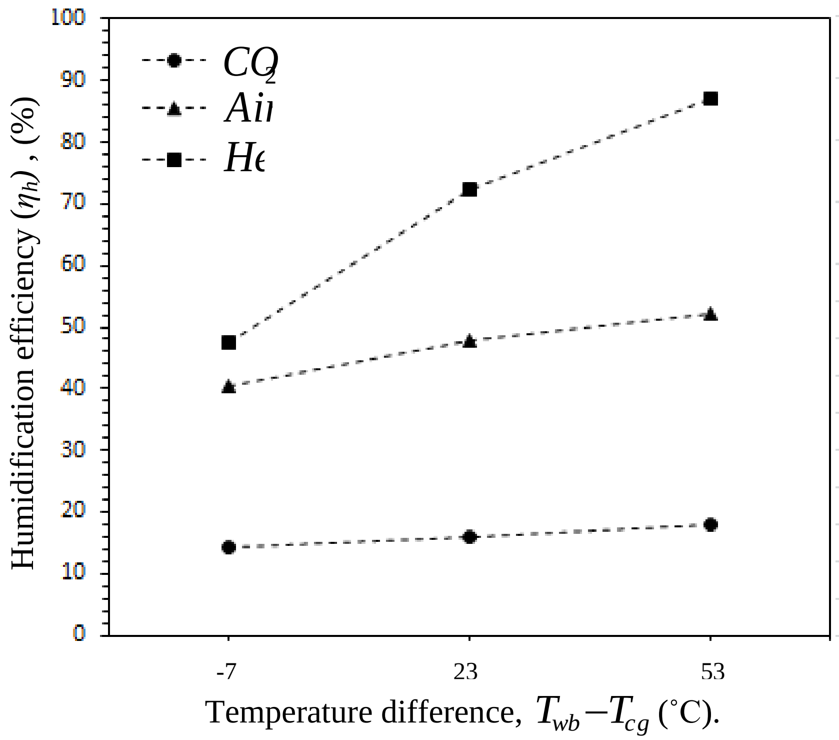


Fig. 7: Humidification efficiency variations as a function of temperature difference between water bed and carrier gas.

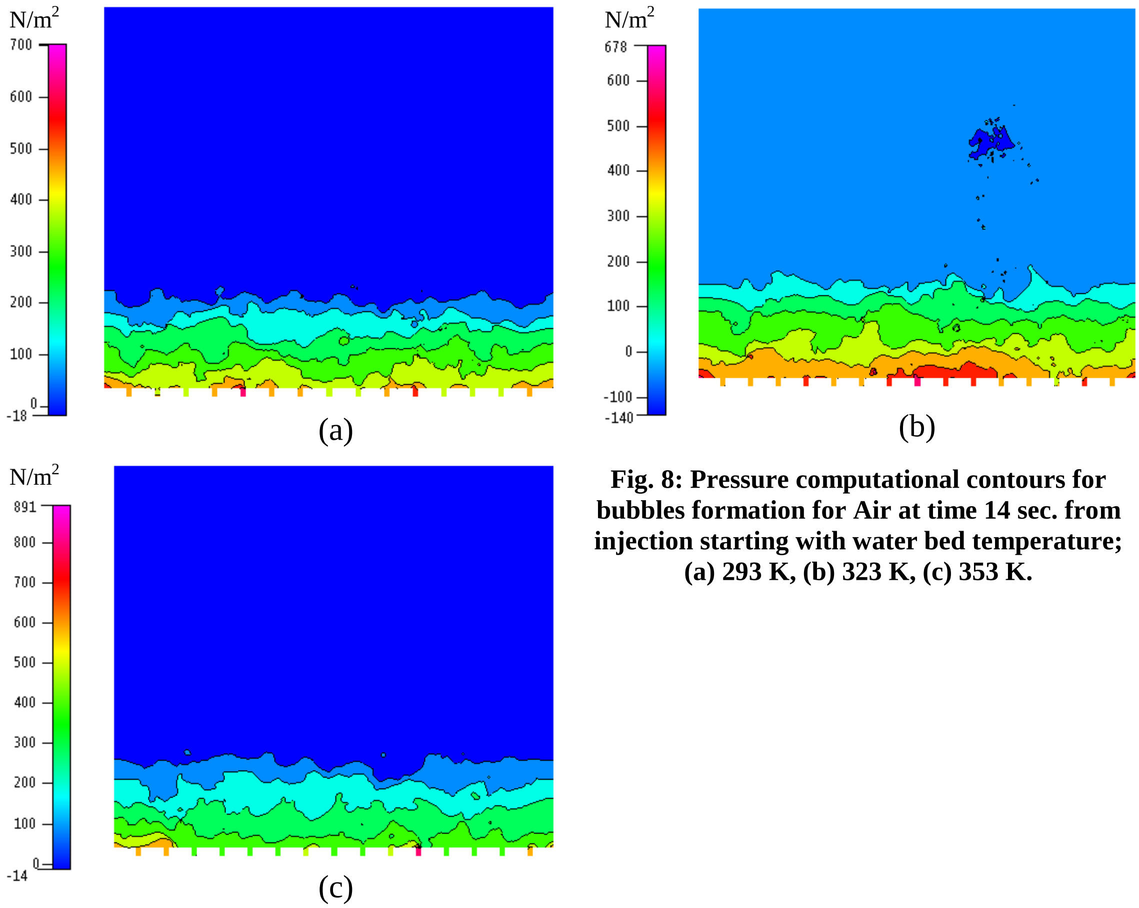
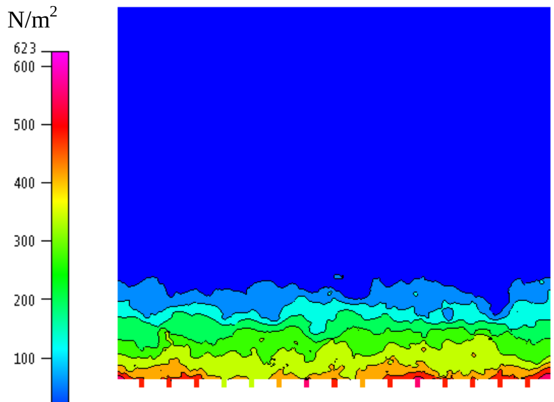


Fig. 8: Pressure computational contours for bubbles formation for Air at time 14 sec. from injection starting with water bed temperature; (a) 293 K, (b) 323 K, (c) 353 K.



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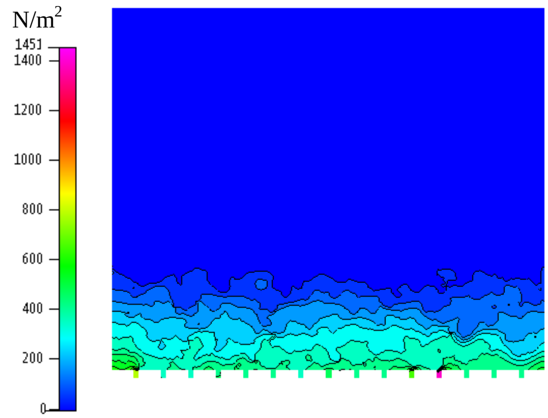

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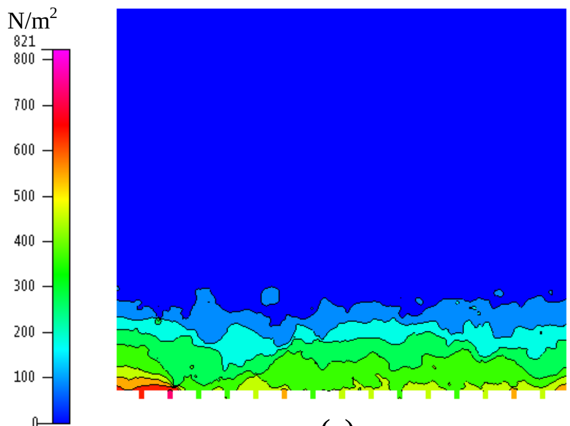

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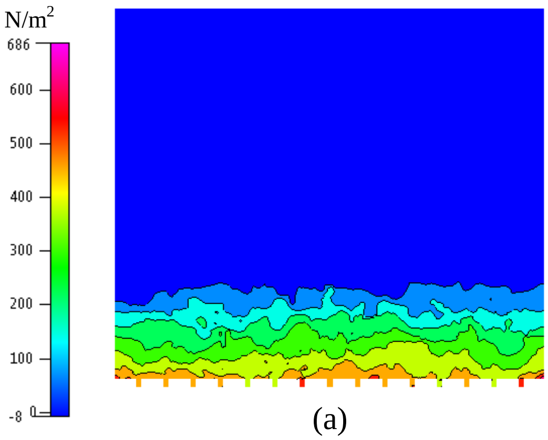
Fig. 9: Pressure computational contours for bubbles formation for Carbon dioxide at time 15 sec. from injection starting with water bed temperature; (a) 293 K, (b) 323 K, (c) 353 K.



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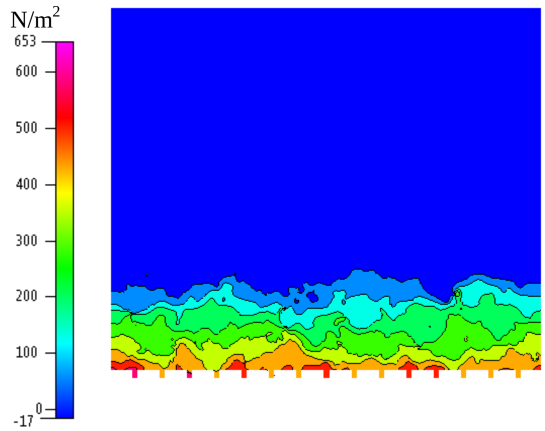

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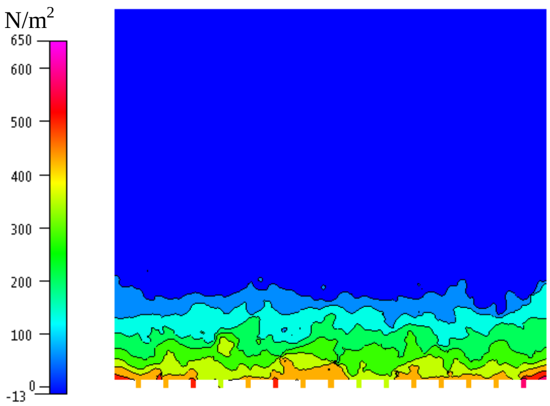

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Fig. 10: Pressure computational contours for bubbles formation for Heluim at time 14 sec. from injection starting with water bed temperature; (a) 293 K, (b) 323 K, (c) 353 K.

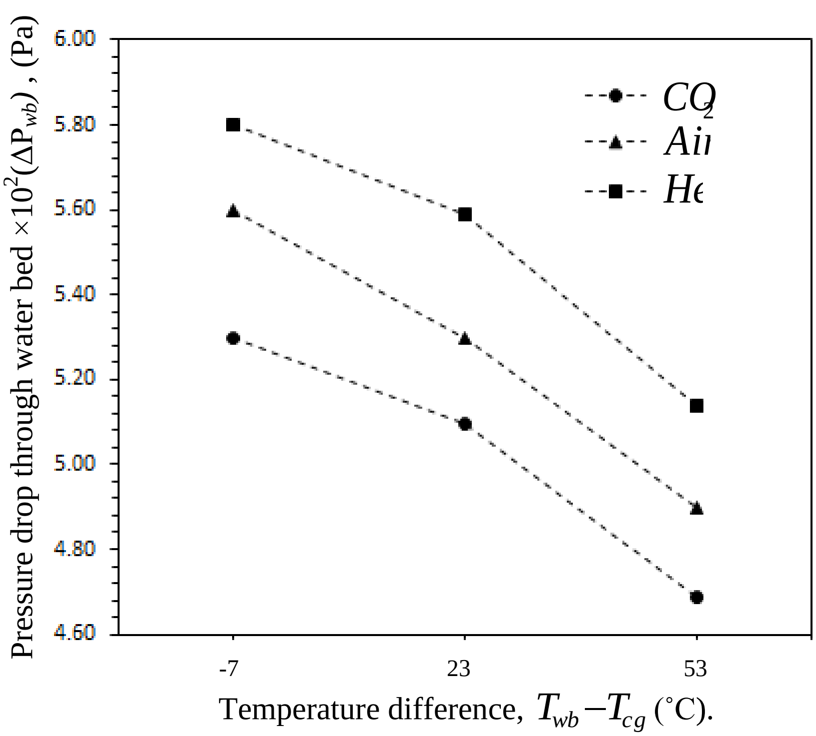


Fig. 11: Pressure drop through water bed variations as a function of temperature difference between

water bed and carrier gas

CARRIER GAS HOLDS UP

The large gas bubbles rise quickly through the water bed than small bubbles [7]. Therefore, the gas residence time decreases and cause to reduce the total gas hold up are calculated using pressure drop as defined by Yu et al. [17]:

$$\varepsilon_{cg} = 1 - \frac{\Delta P}{\rho_w g h_{wb}} \quad (18)$$

where ΔP is the pressure drop in carrier gases through water bed(N/m²), h is the vertical distance between the water bed bottom and thetop surface (m). Figure (12) shows carrier gas holdup through water bed variations as a function of temperature difference between water bed and carrier gas $(T_{wb} - T_{cg})$. The figure illustrates that the decrease of carrier gas molecular weight decreasesits residence time and cause to reduce the total carriergas hold up and increase the humid gas productivity from the humidifier.

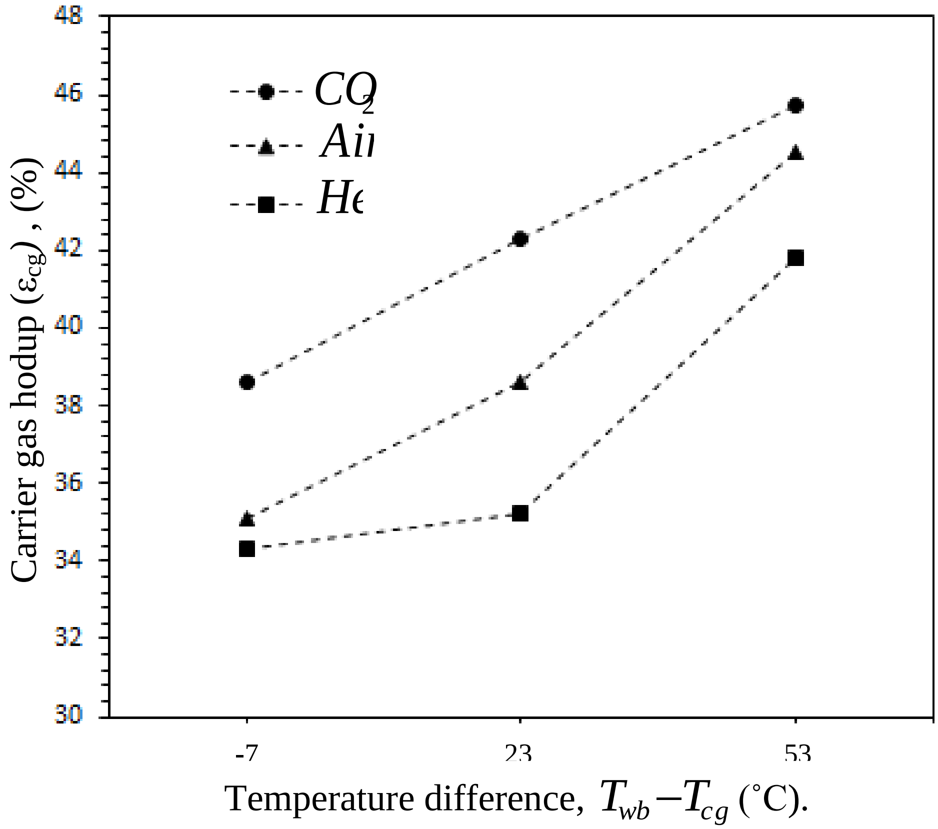


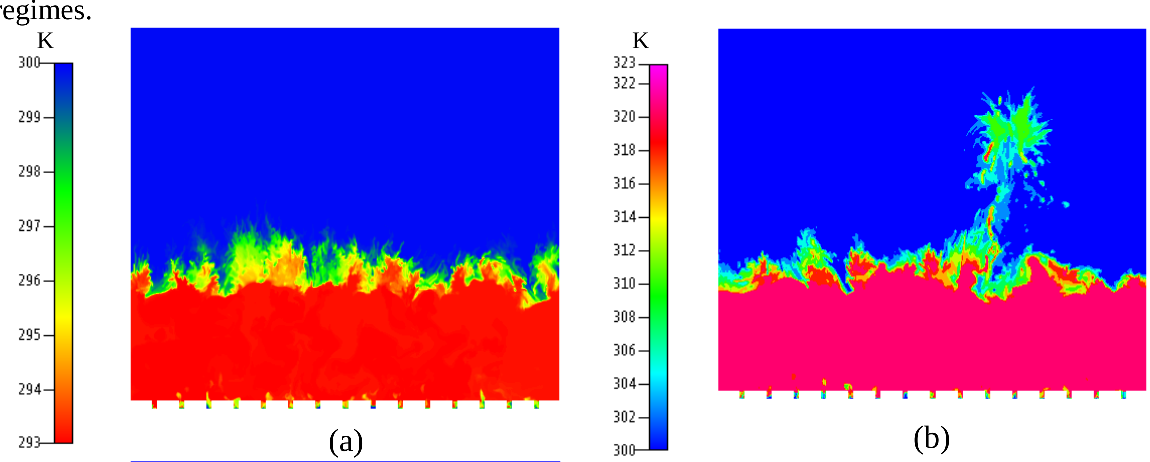
Fig. 12: Carrier gas holdup as a function of temperature difference between water bed and carrier gas.

TEMPERATURE VARIATION

Figures (13-15) give the temperature contours of the gas-liquid flow fieldvariation after certain time period starting from the injection of carrier gas for different values of water bed temperature. It can be found from the figure that the combined effects of injected gas flow and water bed temperature on heat transport, and density variations.These effects are higherfor anincrease of water bed temperature over carrier gas temperature.

HEAT TRANSFER COEFFICIENT

Figure (16) presents the heat transfer coefficient (h_t) with avariation of the temperature difference between water bed and carrier gas $(T_{wb} - T_{cg})$. Carbon dioxide has a high value of heat transfer coefficient. It is interesting to note that the heat transfer coefficients are more than 5 times for carbon dioxide than air flow regimes. They are also less for helium than air, about 50% flow regimes.



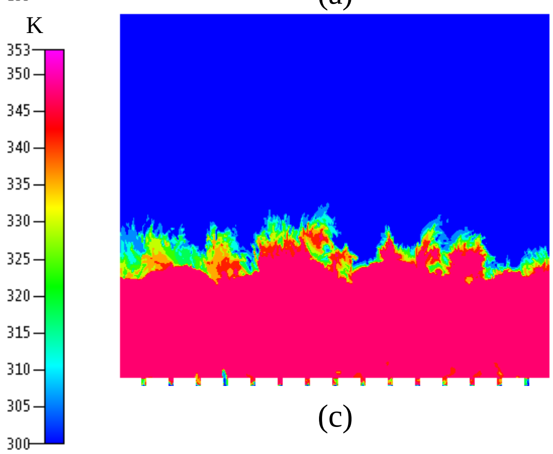
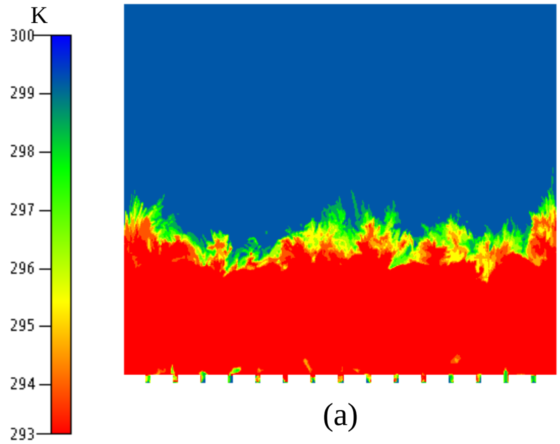
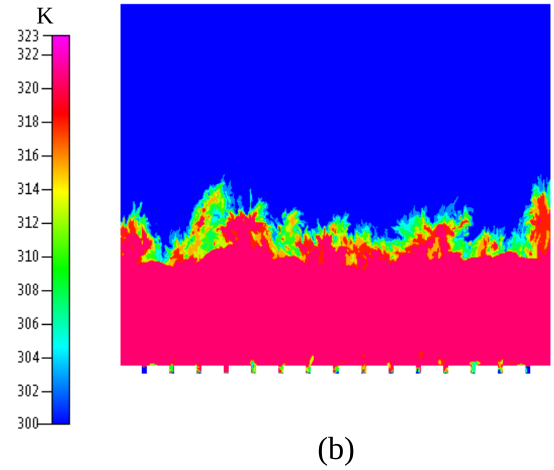


Fig. 13:Temperature computational contours for bubbles formation for Air at time 14 sec. from injection starting with water bed temperature; (a) 293 K, (b) 323 K, (c) 353 K.





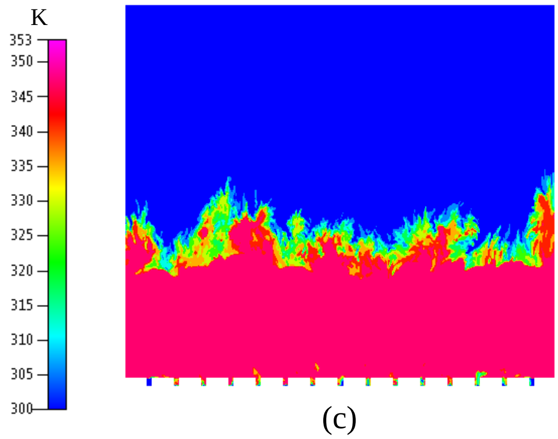
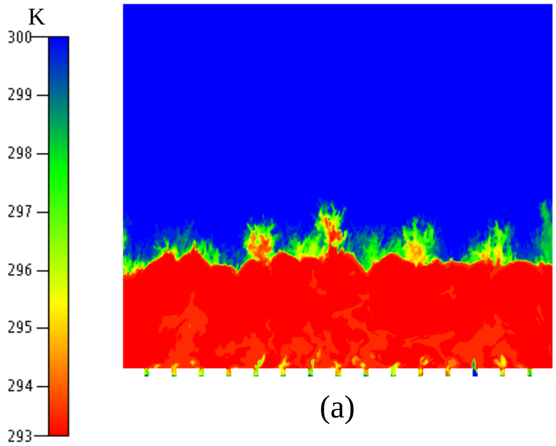


Fig. 14: Temperature computational contours for bubbles formation for Carbon dioxide at time 15 sec. from injection starting with water bed temperature; (a) 293 K, (b) 323 K, (c) 353 K.



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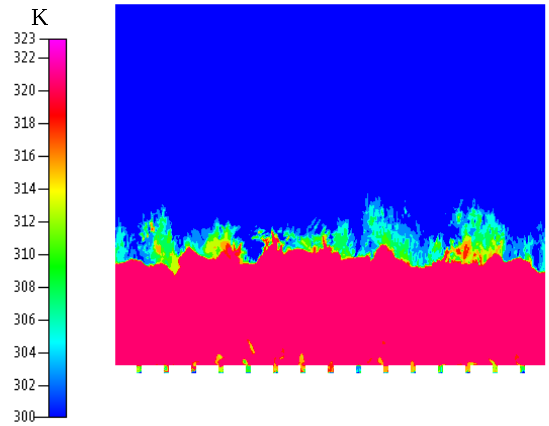

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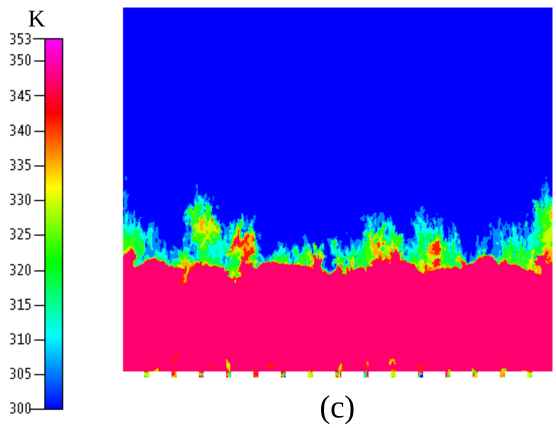

(c)

Fig. 15: Temperature computational contours for bubbles formation for Heluim at time 14 sec. from injection starting with water bed temperature; (a) 293 K, (b) 323 K, (c) 353 K.

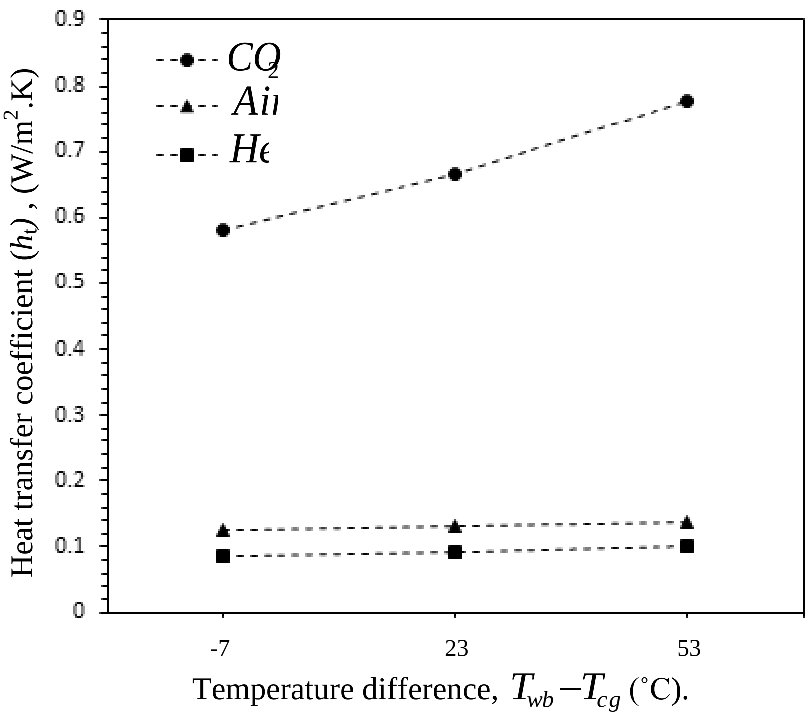

Fig. 16: Heat transfer coefficient as a function of temperature difference between water bed and

carrier gas.

4. CONCLUSIONS

In the current comparative study the influence of the gas physical and thermal properties and water bed temperature on transient flow characteristics, humidification rate and pressure drop in bubbler humidifier based on injected gases through the water bed has been presented. The main conclusions are summarized:

1- The increase in humidification efficiency with the increase in temperature difference between water bed and carrier gas stream.
2- The total carrier gases hold up increases withincreasing gas molecular weight.
3- Lower molecular weight gases such as helium are preferable for higher mass transfer rates while higher molecular weight gases like carbon dioxide are more favorable with respect to heat transfer rates.
4- The obtained maximum humidification efficiency of the helium was about 87%.
5- The increase of carrier gas molecular weight decreases the pressure drop.
6- The pressure drop is about 514 Pa for helium and 472 Pa for carbon dioxide at a water bed temperature 353 K.
7- The current numerical model can predict the heat and mass transfer, so it is considered a good approximation for the experimental data.

NOMENCLATURES

Latin Symbols

F liquid volume fraction

P fluid static pressure, N/m^2

u,v,w velocity in x, y, w respectively, m/s

d diameter, m

h height, m

h_t heat transfer coefficient, W/m^{2}K

k_l mass transfer coefficient, m^2/s

R universal gas constant = 8.3145 *J/mol.K*

D_{AB} mass diffusion, m^2/s.

u_c Liquid circulation velocity, m/s

Greek Letters

□ volume-averaged quantity, m^3

□ density, kg/m^3

□ surface tension between the two fluids, N/m

η efficiency

ε	gas holdup
ω	humidity ratio, kg/kg
α	thermal diffusivity, m^2/s.
Δ	change or difference

Subscripts

1	value of the fluid property (air)
2	value of the fluid property (water)
wb	water bed
h	humid or dumidifier
cg	carrier gas
o	out
in	in
s	saturated
v	vapor
w	water
ih	Injection hole
b	bubble

Acronyms and abbreviations

VOF	Volume-Of-Fluid
SLIC	Single Line Interface Construction Method
PLIC	Piecewise Linear Interface Construction Method
HDH	Humidification-dehumidification

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